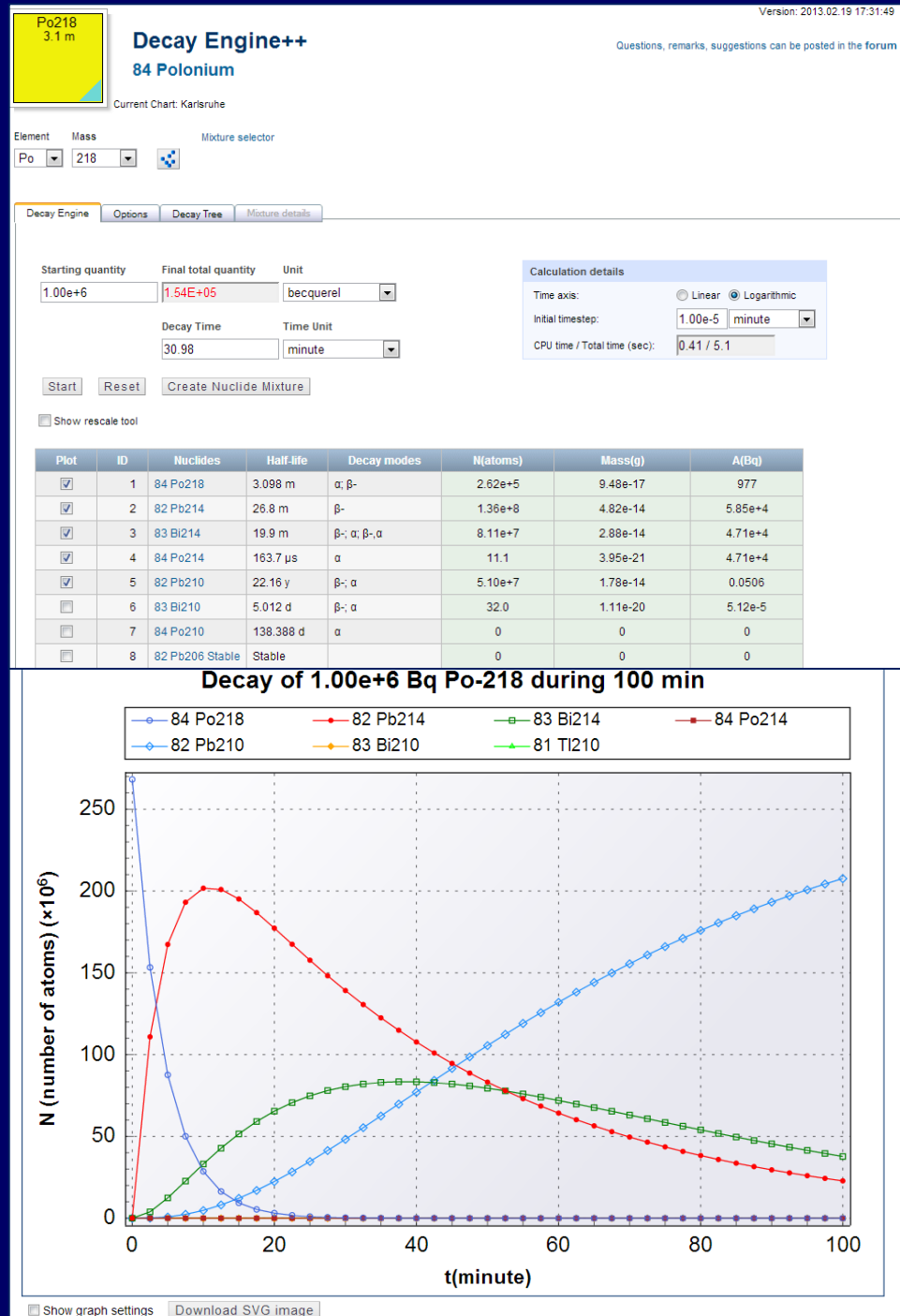


# NUCLEONICA: Decay Engine++

J. MAGILL

Nucleonica GmbH  
c/o European Commission,  
Hermann-von-Helmholtz Platz 1  
76344 Eggenstein-Leopoldshafen, Germany





# Decay Engine++

Some theory

Launching Decay Engine++

Performing calculation with default settings

Exploring calculation results

Selecting options

Plotting results

## Modern Alchemy: Discovery of transmutation, (Soddy 1901)

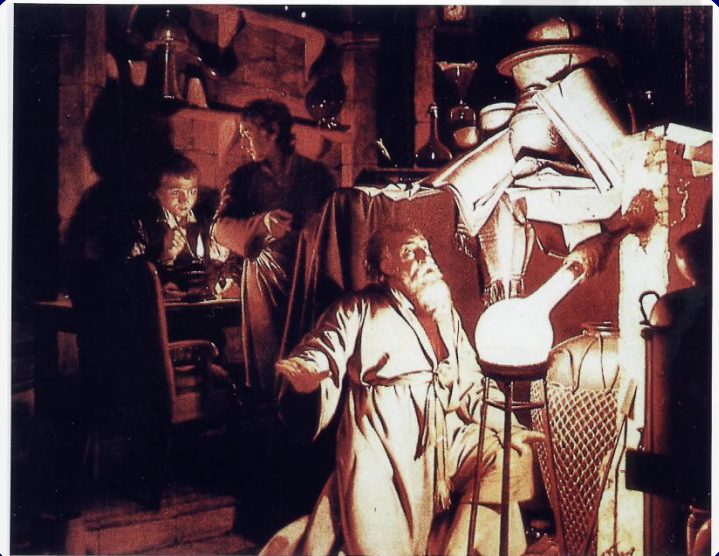
In 1901, twenty-four year-old chemist Frederick Soddy and Ernest Rutherford were attempting to identify a mysterious gas that wafted from samples of radioactive thorium oxide. They suspected that this gas—they called it an “emanation”—held a key to the recently discovered phenomenon of radioactivity. Soddy had passed the puzzling gas over a series of powerful chemical reagents, heated white-hot. When no reactions took place, he came to a startling realization. As he told his biographer many years later....

‘I remember quite well standing there transfixed as though stunned by the colossal import of the thing and blurting out- or so it seemed at the time: “Rutherford, this is transmutation: the thorium is disintegrating and transmuting itself into argon gas“. Rutherford’s reply was typically aware of more practical implications, “For Mike’s sake, Soddy, don’t call it *transmutation*. They’ll have our heads off as alchemists“

\*quoted in *Pioneer*, pp 83-84



Frederic Soddy



Joseph Wright (1734-1797)

Simple radioactive decay..

Basic equation first identified by Rutherford

$$dQ/dt = -kQ \quad (1)$$

Q is the number of atoms, k is the decay constant (probability per unit time that a nucleus will decay):

$$k = \ln 2 / \tau$$

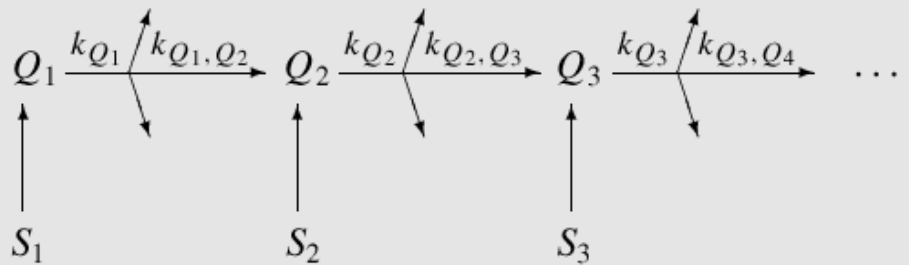
where  $\tau$  is the half-live. Solution of Eq.1...

$$Q(t) = Q(0) e^{-kt} \quad \text{or} \quad Q(t) = Q(0) 2^{-t/\tau}$$

Activity..

$$A(t) = k Q(t)$$

## Successive radioactive decay with branching and source terms



The differential equations governing the above processes:

$$\begin{aligned} \frac{dQ_1}{dt} &= S_1 - k_{Q_1} \cdot Q_1, \\ \frac{dQ_2}{dt} &= S_2 + k_{Q_1, Q_2} \cdot Q_1 - k_{Q_2} \cdot Q_2, \\ \frac{dQ_i}{dt} &= S_i + k_{Q_{i-1}, Q_i} \cdot Q_{i-1} - k_{Q_i} \cdot Q_i, \\ \frac{dQ_n}{dt} &= S_n + k_{Q_{n-1}, Q_n} \cdot Q_{n-1} - k_{Q_n} \cdot Q_i, \end{aligned}$$

*Mr. Bateman, Solution of a system of differential equations, etc. 423*

*The solution of a system of differential equations occurring in the theory of radio-active transformations. By H. BATEMAN, M.A., Trinity College.*

[Read 21 February 1910.]

1. It has been shown by Prof. Rutherford\* that the amounts of the primary substance and the different products in a given quantity of radio-active matter vary according to the system of differential equations,

$$\left. \begin{aligned} \frac{dP}{dt} &= -\lambda_1 P \\ \frac{dQ}{dt} &= \lambda_1 P - \lambda_2 Q \\ \frac{dR}{dt} &= \lambda_2 Q - \lambda_3 R \\ \frac{dT}{dt} &= \lambda_3 R - \lambda_4 T \\ &\dots \dots \dots \end{aligned} \right\} \dots \dots \dots (1).$$

denote the number of atoms of the primary substance and the various products which are present at time  $t$ . Prof. Rutherford has worked out the various cases in which the products in addition to the primary substance, but as if the results may be extended to any without much labour.

The straightforward method is unsymmetrical, the results of the calculations are needed in which are being carried on in radio-activity, but it is worth while to publish a simple and direct method of obtaining the required formulae. Let us assume a set of auxiliary quantities  $p(x), q(x), \dots$  on a variable  $x$  and connected with the  $P(t), Q(t), R(t), \dots$  by the equations,

$$p(x) = \int_0^\infty e^{-xt} P(t) dt, \quad q(x) = \int_0^\infty e^{-xt} Q(t) dt, \dots \dots (2).$$

It is easily seen that

$$\begin{aligned} \int_0^\infty e^{-xt} \frac{dP}{dt} dt &= -P(0) + x \int_0^\infty e^{-xt} P(t) dt \dots \dots \dots (3), \\ &= -P_0 + xp, \end{aligned}$$

\* Radio-activity, 2nd edition, p. 582.



H. Bateman

Exact solution:

$$Q_n(t) = \sum_{i=1}^{i=n} \left[ \left( \prod_{j=1}^{j=n-1} k_{j,j+1} \right) \times \sum_{j=i}^{j=n} \left( \frac{Q_i(0) e^{-k_j t}}{\prod_{\substack{p=i \\ p \neq j}}^n (k_p - k_j)} + \frac{S_i (1 - e^{-k_j t})}{k_j \prod_{\substack{p=i \\ p \neq j}}^n (k_p - k_j)} \right) \right]$$

For  $S_i = 0$ :

$$Q_n(t) = \prod_{j=1}^{j=n-1} k_{j,j+1} \sum_{j=i}^{j=n} \frac{Q_i(0) e^{-k_j t}}{\prod_{\substack{p=i \\ p \neq j}}^n (k_p - k_j)}$$

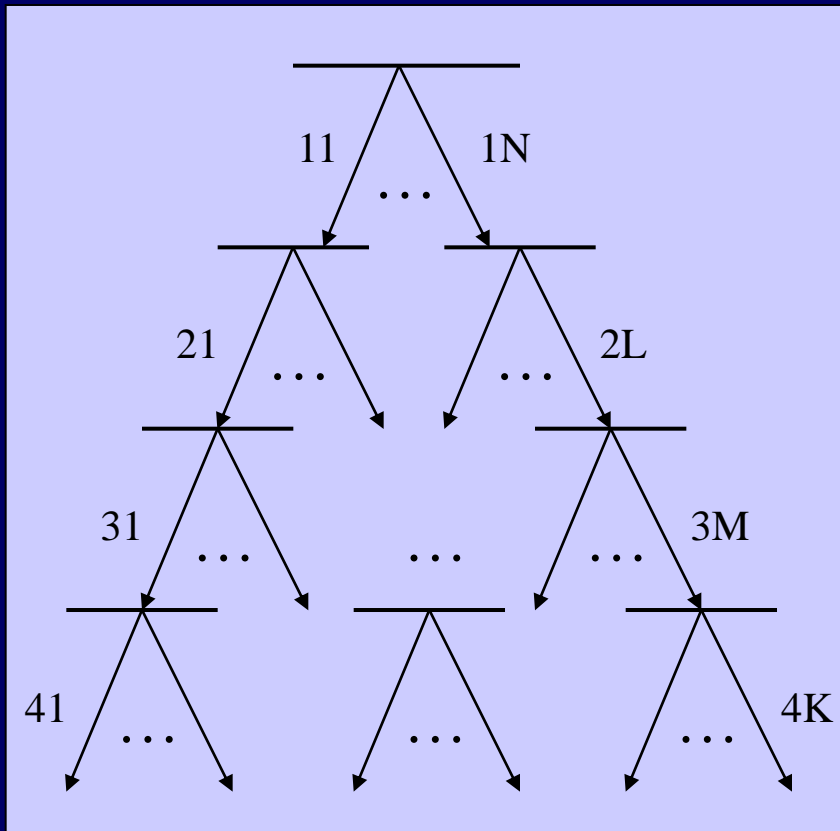
First few terms...

$$Q_1 = Q_1(0) e^{-k_1 t}$$

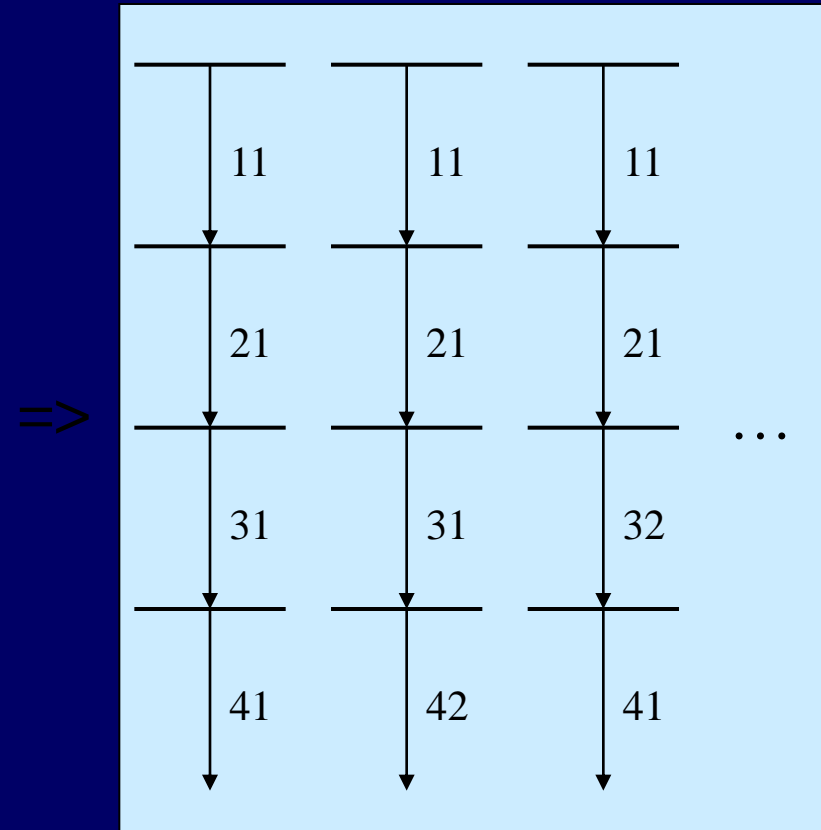
$$Q_2 = k_{1,2} \left\{ \frac{Q_1(0) e^{-k_1 t}}{k_2 - k_1} + \frac{Q_1(0) e^{-k_2 t}}{k_1 - k_2} \right\}$$

$$Q_3 = k_{1,2} k_{2,3} \left\{ \frac{Q_1(0) e^{-k_1 t}}{(k_2 - k_1)(k_3 - k_1)} + \frac{Q_1(0) e^{-k_2 t}}{(k_1 - k_2)(k_3 - k_2)} + \frac{Q_1(0) e^{-k_3 t}}{(k_1 - k_3)(k_2 - k_3)} \right\}$$

## Decay Tree



## Linear Chains



$$\text{Prod}_1 = \text{BR}_{11} \text{BR}_{21} \text{BR}_{31} \text{BR}_{41}$$

Applications

- Nuclide Explorer
- Mass Activity Calculator
- Mass Activity Converter
- Decay Engine
- Decay Engine++**
- Dosimetry and Shielding
- Range and Stopping Power
- In Silico Dosimetry
- webKORIGEN
- Decay Engine for Large Nuclide Sets
- Universal Nuclide Chart
- e-Ship: radiological transport assistant
- Transport and Packaging
- Nuclide Mixtures
- Nucleonica Scripting
- Radiological Dispersion Module
- Gamma Spectrum Generator
- Gamma Spectrum Generator Pro
- Virtual Cloud Chamber
- Geant4 Dosimetry
- Cambio file converter
- WESPA
- WESPA2
- Gamma Library
- webGraph

My Preferences Networking Nuclear Science Help New Browser Logout

**Application Centre**

- » Mass Activity Calculator
- » **New: Mass Activity Converter**
- » Decay Engine
- » **New: Decay Engine++**
- » Dosimetry & Shielding
- » Range & Stopping Power
- » In Silico Dosimetry
- » webKORIGEN
- » Decay Engine for Large Nuclide Sets
- » Universal Nuclide Chart
- » Transport & Packaging
- » **New: e-Ship: radiological transport assistant**
- » Nuclide mixtures
- » Nucleonica Scripting
- » Radiological Dispersion Module
- » Gamma Spectrum Generator
- » Gamma Spectrum Generator Pro
- » Virtual Cloud Chamber
- » Geant4 Dosimetry
- » easy Monte Carlo
- » Cambio file Converter

Welcome, Joseph

My Settings Administration Networking

**To launch the Decay Engine**

click on Decay Engine in the Application Center list.....

or

choose Decay Engine from the Applications dropdown list....

Search

Search

chart: Karlsruhe

tion

Search

nucleonica [wiki]

Pu241 with daughters

# Internet Explorer only!

Logged in as: aberizov Home Search Forum Calculator Disclaimer

nucleonica ... web driven nuclear science

Views Applications My Preferences Help New Alerts

z  
N

Select

Element: Mass:  
Po 218

Zoom

View: 5

Select colour theme:

Karlsruhe

☒ alpha  
☒ beta -  
☒ beta +  
☒ IT  
☒ n  
☒ SF  
☒ p  
☒ ec  
☒ CE

☒ stable

All None

Background

Rn216 45 $\mu$ s	Rn217 540 $\mu$ s	Rn218 35 ms	Rn219 3.98 s	Rn220 55.8 s	Rn221 25 m	Rn222 3.82 d
At215 100 $\mu$ s	At216 300 $\mu$ s	At217 32.3 ms	At218 1.5 s	At219 54 s	At220 3.71 m	At221 2.3 m
Po214 1.6E2 $\mu$ s	Po215 1.78 ms	Po216 150 ms	Po217 1.47 s	Po218 3.1 m	Po219 2 m	Po220 40 s
Bi213 45.59 m	Bi214 19.9 m	Bi215 36.9 s 7.4 m	Bi216 2.17 m	Bi217 1.84 s		
Pb212 10.64 h	Pb213 10.2 m	Pb214 26.8 m	Pb215 36 s			

130 131 132 133 134 135 136

Ground state: 3127 nuclides from 3127 Metastable: 769 nuclides from 769 Total: 3896 nuclides from 3896

Highlight daughters  
Show decay chain  
Reference Data  
Element Information  
Decay Engine  
Dosimetry & Shielding  
Get image  
Remove red border  
Cancel

## To launch the Decay Engine

select nuclide of interest in the Nuclide Explorer page.....

then

click right mouse button over it .....

and

choose Decay Engine from the list, which will appear

.....

# Typical calculation...

nucleonica ... web

Applications Data Knowledge My Preferences Print

Po218 3.1 m

## Decay Engine++

84 Polonium

Current Chart: Karlsruhe

Element Mass Mixture selector

Po 218

Decay Engine Options Decay Tree Mixture details

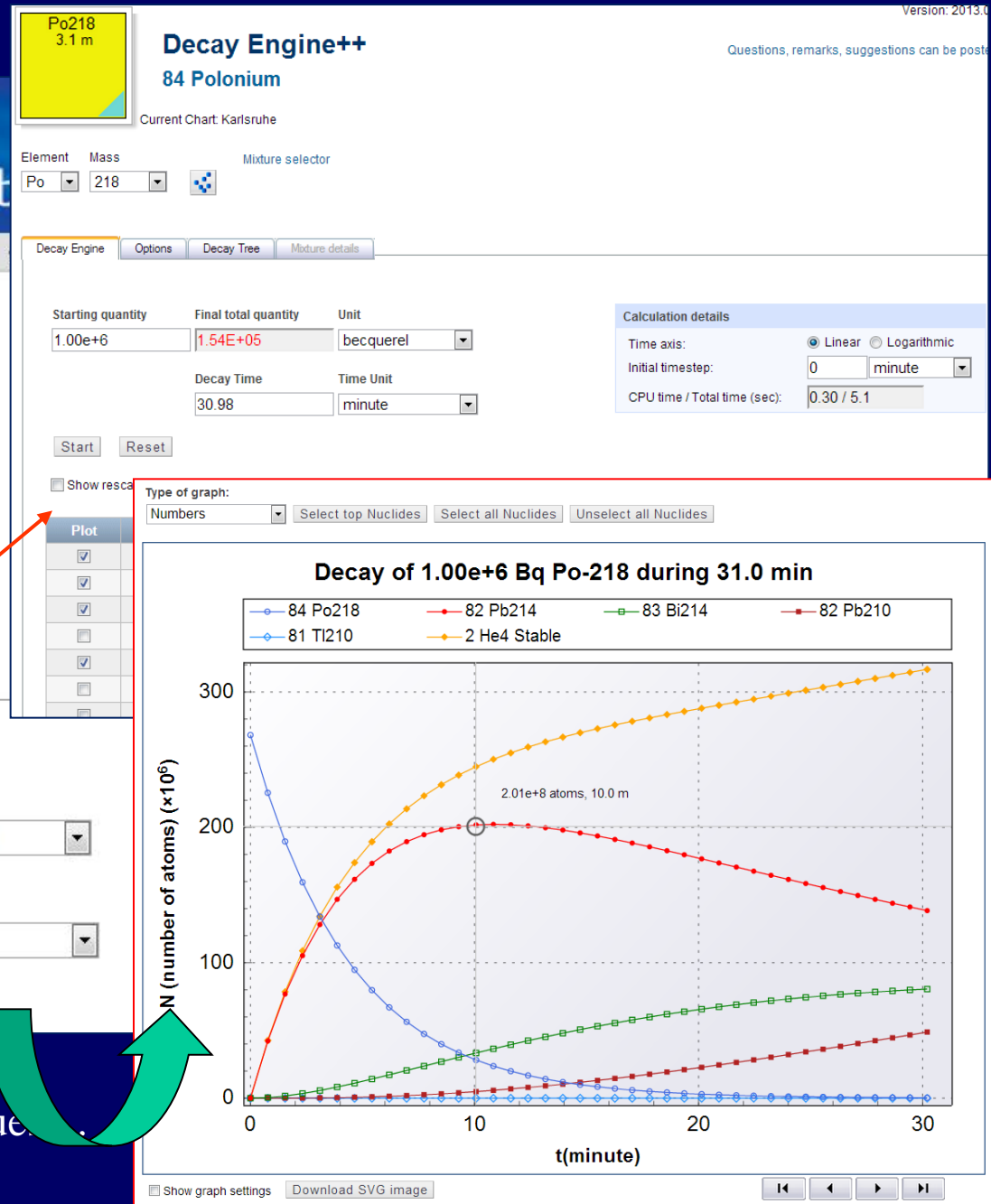
Starting quantity Final total quantity Unit

1.00e+6 1.54E+05 becquerel

Decay Time Time Unit

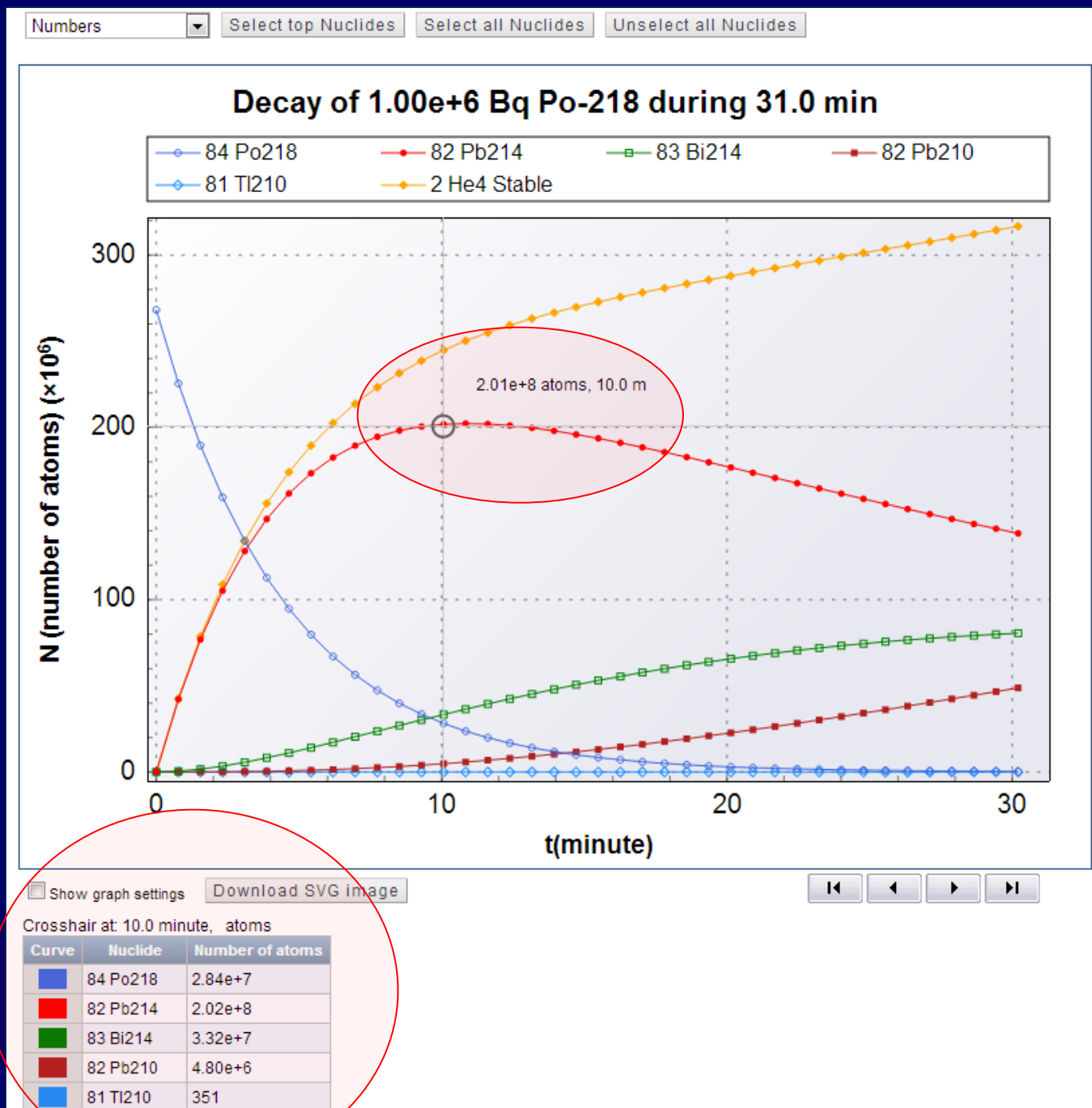
30.98 minute

Start Reset



Start a calculation using default value...

Slider  
control for  
easy reading  
graph  
values...



Element Info in  
Nucleonica wiki

Nuclide  
selection  
tools

Po	218
Pr	198
Pt	199 m
Pu	200
Ra	201
Rb	201 m
Re	202
Rf	203
Rg	203 m
Rh	204
Rn	205
Ru	205 m
S	206
Sb	207
Sc	207 m
Se	208
Sg	209
Si	210
Sm	211
Sn	211 m
Sr	212
Ta	212 m
Tb	213
Tc	214
Te	215
Th	216
Ti	217
Tl	218
Tm	219
U	220

Set time

Set  
quantity

nucleonica ... web d

Applications Data Knowledge My Preferences Print Network

Po218  
3.1 m

## Decay engine

### 84 Polonium

Current Chart: Karlsruhe

Element: Po Mass: 218

Decay Engine Options Decay Tree Mixture details

Time Unit: Minutes Decay Time: 30.98

Starting quantity: 1.0000e+6 Final quantity: ??? Unit: Becquerel

Start Reset

Type of graph: Activities

Polonium Po - NucleonicaWiki - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address: http://www.nucleonica.net:81/wiki/index.php/Polonium\_Po

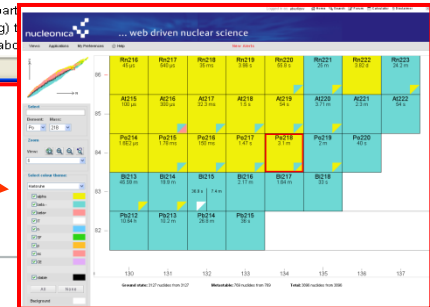
nucleonica [wiki]

Polonium Po

Polonium

(Poland, native country of Mme. Curie). Polonium was the first element discovered by Mme. Curie in 1898 while seeking the cause of radioactivity of pitchblend from Joachimsthal, Bohemia. The electroscope showed it separating with bismuth. Polonium is also called Radium F. Polonium is a very rare natural element. Uranium ores contain only about 100 micrograms of the element per ton. Its abundance is only about 0.2% of that of radium. In 1934, it was found that when natural bismuth ( $^{209}\text{Bi}$ ) was bombarded by neutrons,  $^{210}\text{Bi}$ , the parent of polonium, was obtained. Milligram amounts of polonium may now be prepared this way, by using the high neutron fluxes of nuclear reactors. Polonium-210 is a low-melting, fairly volatile metal, 50% of which is vaporized in air in 45 hours at 55°C. It is an alpha emitter with a half-life of 138.39 days. A milligram emits as many alpha particles as a 100-watt light bulb. The temperature of the element is about 254°C.

Mixture selector



### Calculation details

Time axis: ☐ Linear ☒ Logarithmic

Initial timestep: 1.00e-5 minute

CPU time / Total time (sec): 0.41 / 5.1

Po218  
3.1 mDecay Engine++  
84 Polonium

Questions, remarks, suggestions can be posted in the forum

Current Chart: Karlsruhe

Element Mass Mixture selector  
Po 218

Decay Engine Options Decay Tree Mixture details

Starting quantity Final total quantity Unit  
1.00e+6 1.54E+05 becquerelDecay Time Time Unit  
30.98 minute

Start Reset Create Nuclide Mixture

☐ Show rescale tool

## Calculation details

Time axis: ☐ Linear ☒ Logarithmic  
Initial timestep: 1.00e-5 minute  
CPU time / Total time (sec): 0.41 / 5.1

Plot	ID	Nuclides	Half-life	Decay modes	N(atoms)	Mass(g)	A(Bq)
<input checked="" type="checkbox"/>	1	84 Po218	3.098 m	$\alpha$ ; $\beta^-$	2.62e+5	9.48e-17	977
<input checked="" type="checkbox"/>	2	82 Pb214	26.8 m	$\beta^-$	1.36e+8	4.82e-14	5.85e+4
<input checked="" type="checkbox"/>	3	83 Bi214	19.9 m	$\beta^-$ ; $\alpha$ ; $\beta^-$ , $\alpha$	8.11e+7	2.88e-14	4.71e+4
<input checked="" type="checkbox"/>	4	84 Po214	163.7 $\mu$ s	$\alpha$	11.1	3.95e-21	4.71e+4
<input checked="" type="checkbox"/>	5	82 Pb210	22.16 y	$\beta^-$ ; $\alpha$	5.10e+7	1.78e-14	0.0506
<input type="checkbox"/>	6	83 Bi210	5.012 d	$\beta^-$ ; $\alpha$	32.0	1.11e-20	5.12e-5
<input type="checkbox"/>	7	84 Po210	138.388 d	$\alpha$	0	0	0
<input type="checkbox"/>	8	82 Pb206 Stable	Stable		0	0	0
<input type="checkbox"/>	9	81 Ti206	4.202 m	$\beta^-$	0	0	0
<input type="checkbox"/>	10	80 Hg206	8.15 m	$\beta^-$	0	0	0
<input checked="" type="checkbox"/>	11	81 Ti210	1.30 m	$\beta^-$ ; $\beta^-$ , n	1.09e+3	3.80e-19	9.68
<input type="checkbox"/>	12	82 Pb209	3.253 h	$\beta^-$	0.651	2.26e-22	3.85e-5
<input type="checkbox"/>	13	83 Bi209	1.9E+19 y	$\alpha$	0	0	0
<input type="checkbox"/>	14	81 Ti205 Stable	Stable		0	0	0
<input type="checkbox"/>	15	85 At218	1.5 s	$\alpha$ ; $\beta^-$	0	0	0
<input type="checkbox"/>	16	86 Rn218	35 ms	$\alpha$	0	0	0
<input type="checkbox"/>	17	2 He4 Stable	Stable		3.19e+8	2.12e-15	0

Click on the column title to arrange the data in ascending /descending order on the parameter chosen

Version: 2013.03.08 13:28:50

**Po218**  
 3.1 m

## Decay Engine++

### 84 Polonium

Current Chart: Karlsruhe

Questions, remarks, suggestions can be posted in the [forum](#)

Element Po Mass 218

Mixture selector

**Mode of operation**

☒ Time  
☐ Date

Universal time, UTC

---

**Calculation details**

Number of timesteps:

Accuracy Factor:

Significant figures:

Number of linear chains: 23

Selected columns of the decay result grid

General	Quantities	Handling	Disintegrations
<input checked="" type="checkbox"/> Half-lives	<input checked="" type="checkbox"/> Numbers	<input type="checkbox"/> Isotopic Power $\alpha$	<input type="checkbox"/> Disintegrations
<input checked="" type="checkbox"/> Decay Mode	<input checked="" type="checkbox"/> Masses	<input type="checkbox"/> Isotopic Power $\alpha+\beta$	<input type="checkbox"/> $\alpha$ particles
<input type="checkbox"/> Branching ratio	<input checked="" type="checkbox"/> Activities	<input type="checkbox"/> Isotopic Power $\alpha+\beta+\gamma$	<input type="checkbox"/> $\beta^-$ , $\bar{\nu}$ particles
	<input type="checkbox"/> Activity ratio	<input type="checkbox"/> $\gamma$ emission rate	<input type="checkbox"/> $ec/\beta^+$ , $\nu$
	<input type="checkbox"/> Activities ( $\alpha$ )	<input checked="" type="checkbox"/> $\gamma$ dose rate ( $\mu\text{Sv/h}$ ) @ <input type="text" value="100"/> cm	
	<input type="checkbox"/> Activities ( $\beta$ )	<input type="checkbox"/> $\gamma$ dose ( $\mu\text{Sv}$ )	
	<input type="checkbox"/> Released energy(J)	<input type="checkbox"/> Spontaneous Fission Rate	
	<input type="checkbox"/> Released energy(MeV)	<input type="checkbox"/> sf neutron emission rate(/s)	
	<input type="checkbox"/> Average Q-value(MeV)		
	<input type="checkbox"/> Ingestion Radiotoxicity		
	<input type="checkbox"/> Inhalation Radiotoxicity		

Radiotoxicity (Sv) = Activity  $\cdot$   $e(50)$ , where  
 $e(50)$  - effective dose coefficient, which  
 accounts for radiation and tissue weighting  
 factors, metabolic and biokinetic information

the heat generated per unit time by  
 the decay radiations (W)

# Date mode:

Version: 2013.0

**Ra226**  
 1.6E3 y

## Decay Engine++

### 88 Radium

Current Chart: Karlsruhe

Questions, remarks, suggestions can be posted here

Element **Ra** Mass **226**

Mixture selector

Decay Engine

Options

Decay Tree

Mixture details

**Starting quantity**

**Final total quantity**

**Unit**

**Starting date / time**

**Final date / time**

**Time span**

<<

February

2013

>>

Mon	Tu	We	Th	Fr	Sa	Su
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28			

:  :

☐ Show rescale tool

Plot	ID	N
<input checked="" type="checkbox"/>	1	88 Ra2
<input checked="" type="checkbox"/>	2	86 Rn2
<input checked="" type="checkbox"/>	3	84 Po2

Decay modes	N(atoms)	Mass(g)	A(Bq)
2β <sup>-</sup> ; C14	7.25e+16	2.72e-5	9.95e+5
	4.74e+11	1.75e-10	9.95e+5
β <sup>-</sup>	2.67e+8	9.66e-14	9.95e+5

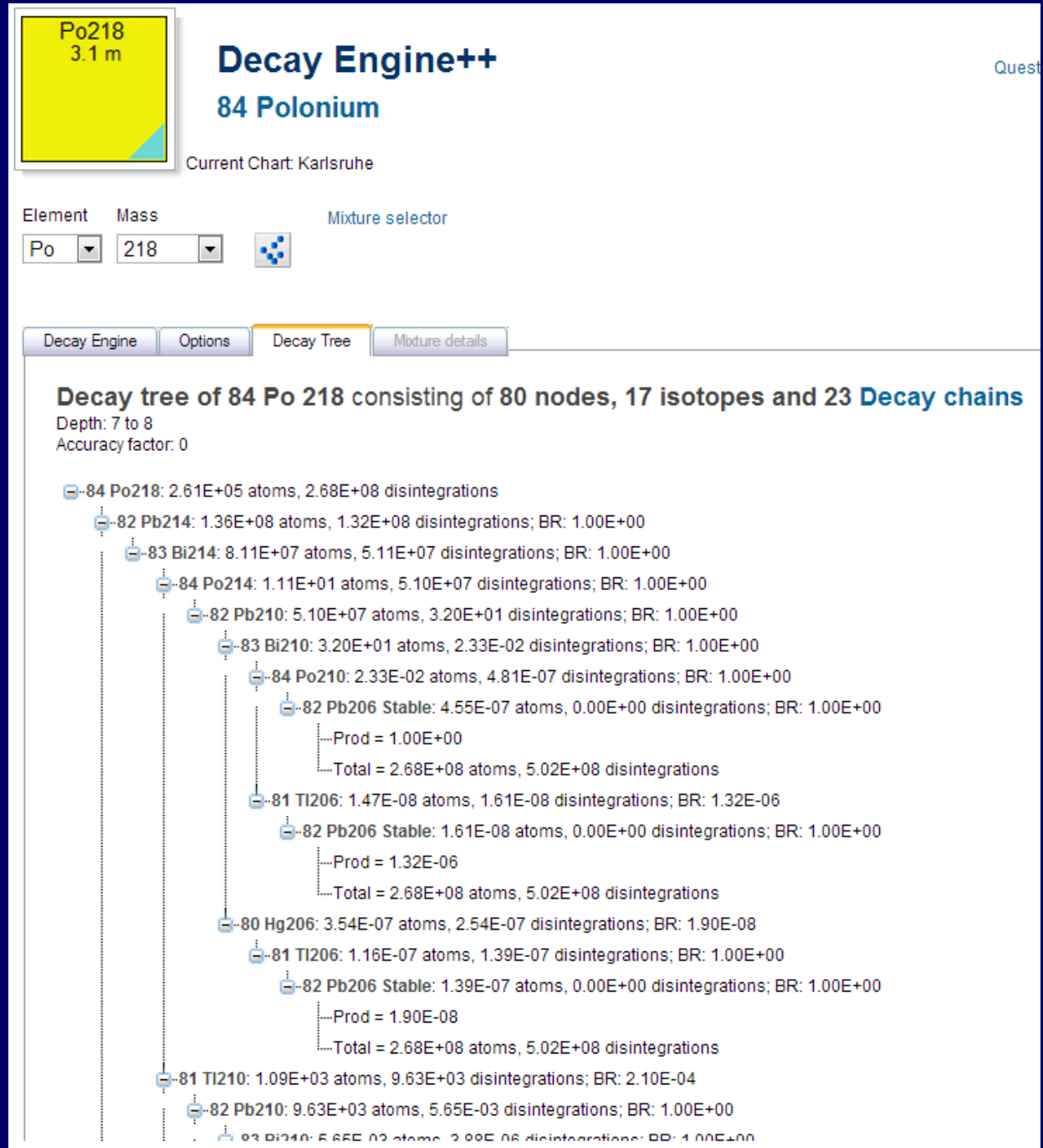
**Calculation details**

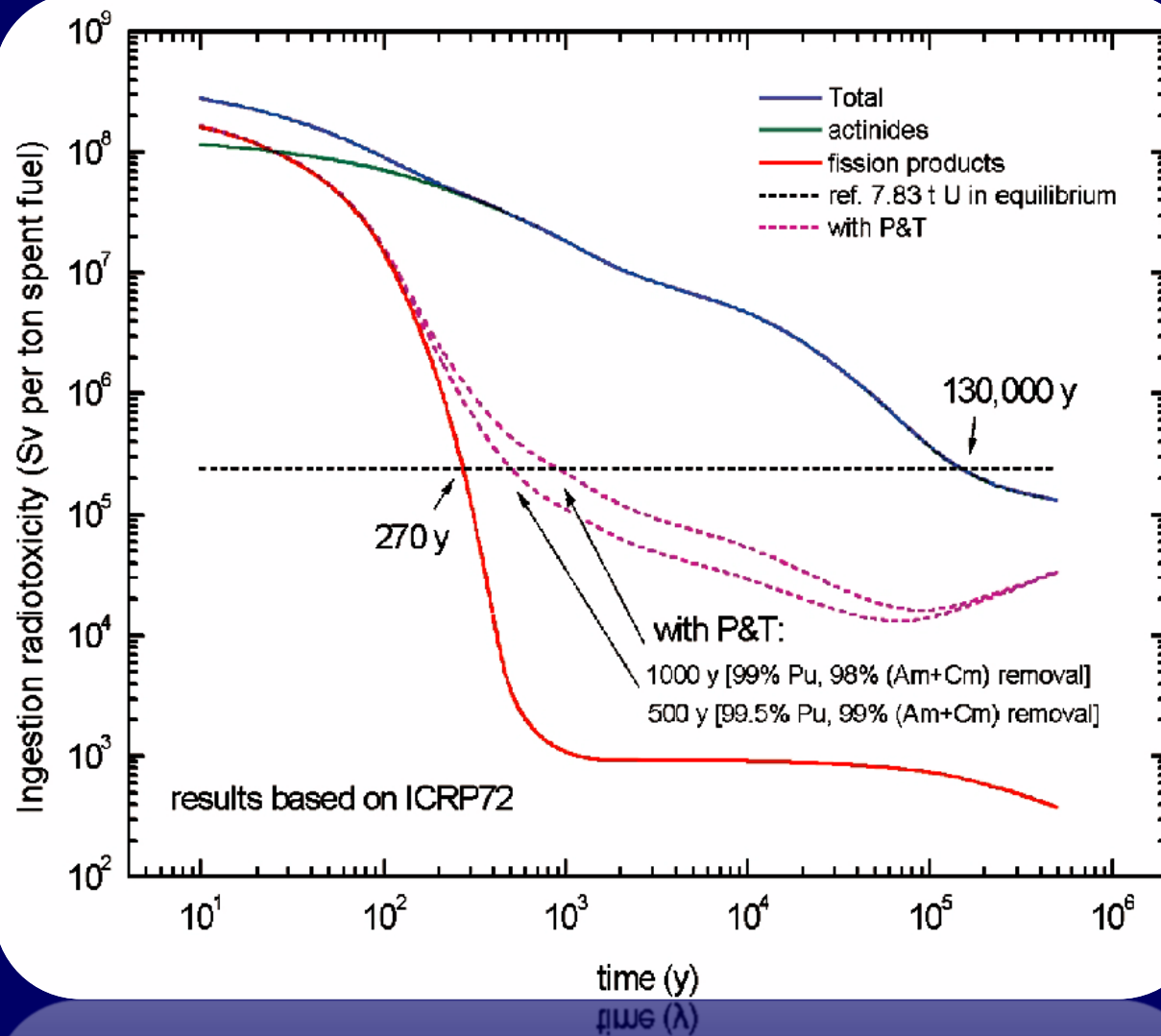
Time axis: ☒ Linear ☐ Logarithmic

Initial timestep:

CPU time / Total time (sec):

Decay Tree tab  
showing details of  
decay process – linear  
chains, etc.





# Decay Engine++

## Some theory

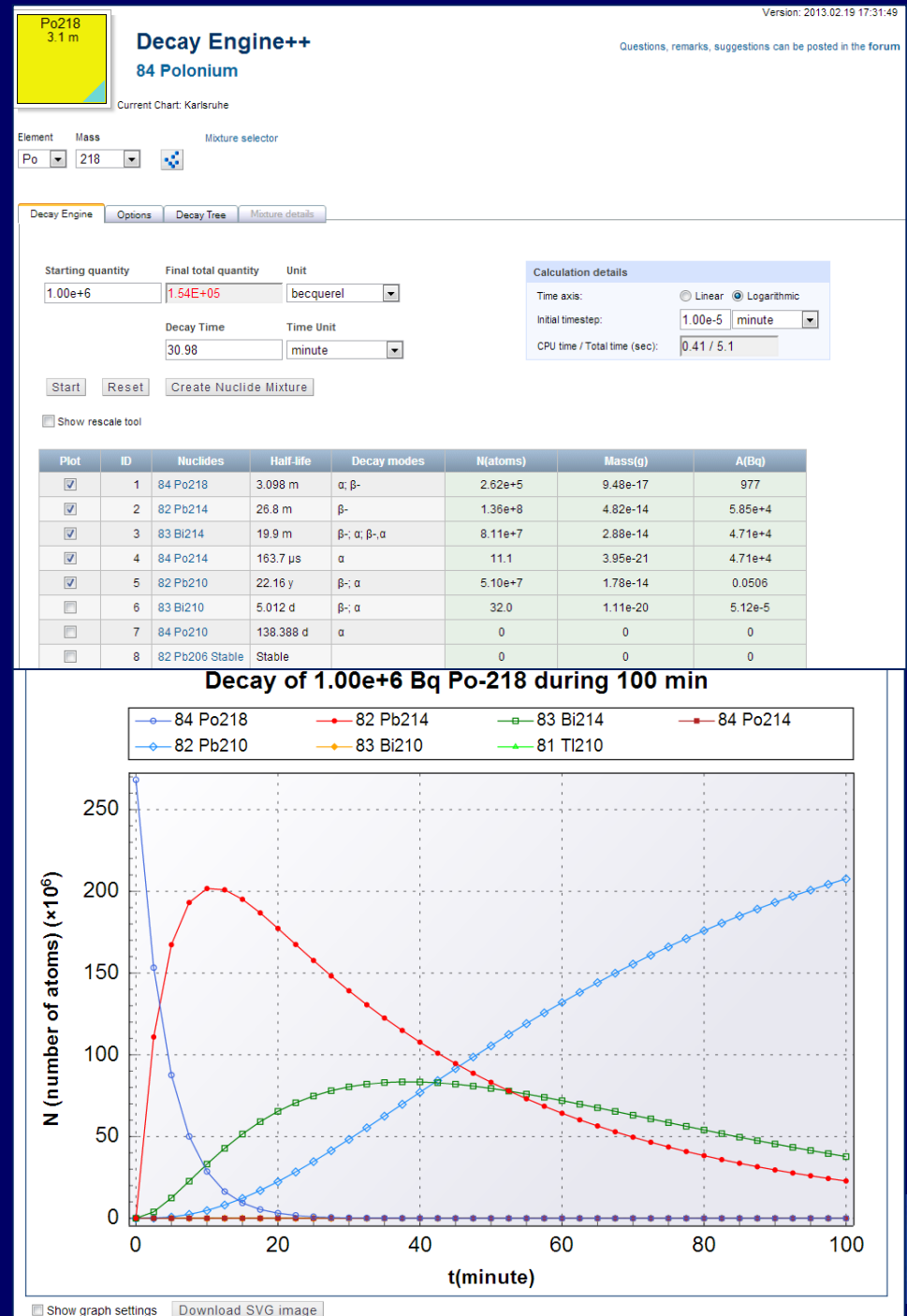
## Launching Decay Engine++

## Performing calculation with default settings

## Exploring calculation results

## Selecting options

## Plotting results



Thanks!



# Exercises - Decay Engine++

1. At  $t=0$  there are 10 Ci of Sr-90. What will be the activity of Y-90 after 5 years?  
Ans. 8.87 Ci
2. What is the time required for the activity of Na-24 to diminish to 1% of its initial value? Ans. 4.14 d
3. What initial mass of F-18 is required in order that there are 3 mg remaining after 16 hours?(1.3g)
4. Calculate the activity of a Tl-204 source today that was calibrated at 1  $\mu$ Ci on Sept. 3, 1993. (30.2 nCi, 22 Oct. 2012)
5. What is the activity of a Rn-222 sample in an ore sample containing 3g uranium (Rn-222 is produced by U-238) (37 kBq at  $1e6$  years)